

## Wind Energy

### Technology Description

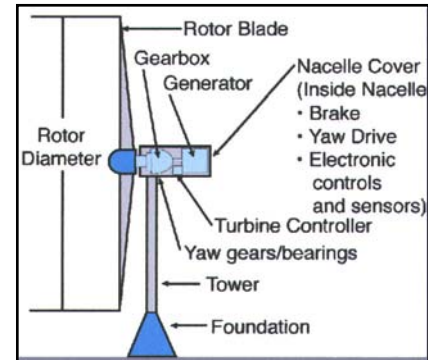
Wind-turbine technology converts the kinetic energy in the wind to mechanical energy and ultimately to electricity. Grid-connected wind power reduces GHG emissions by displacing the need for natural gas- and coal-fired generation. Village and off-grid applications are important for displacing diesel generation and for improving quality of life, especially overseas.

#### System Concepts

- The principle of wind energy conversion is simple: Wind passing over the blade creates lift, producing a torque on the rotor shaft that turns a gearbox. The gearbox is coupled to an electric generator that produces power at the frequency of the host power system. Some new innovative designs use low-speed generators, which eliminate the need for a gearbox.

#### Representative Technologies

- Two major design approaches are being used: (1) typical of historic European technology—three-bladed, up-wind, stiff, heavy machines that resist cyclic and extreme loads, and (2) lightweight, flexible machines that bend and absorb loads, primarily being developed by U.S. designers. Several alternative configurations within each approach are being pursued.



### Technology Applications

- Thirty-seven states have land area with good winds (13 mph annual average at 10 m height, wind Class 4, or better).
- For wind-farm or wholesale power applications, the principal competition is natural gas for new construction and natural gas in existing units for fuel saving. Utility restructuring is a critical challenge to increased deployment in the near-term because it emphasizes short-term, low capital-cost alternatives and lacks public policy to support deployment of sustainable technologies such as wind energy.

### Current Status

- Wind technology is competitive today in bulk power markets with support from the production tax credit, and in high-value niche applications or markets that recognize noncost attributes.
- Current performance is characterized by leveled costs of 4 to 6¢/kWh (depending on resource intensity and financing structure), capacity factors of 30 to 40 percent, availability of 95 to 98%, total installed project costs ("overnight" – not including construction financing) of \$800 to \$1,100/kW, and efficiencies of 65% to 75% of the theoretical (Betz limit) maximum.
- The worldwide annual market growth rate for wind technology is at a level of 30% with new markets opening in many developing countries. Domestic public interest in environmentally responsible electric generation technology is reflected by new state energy policies and in the success of "green marketing" of wind power across the country.
- Preliminary estimates are that installed capacity at the end of 2001 was 4,260 MW in the United States, and 23,300 MW worldwide; compared to 2,550 MW in the United States and 17,653 worldwide in 2000; and 2,450 MW in the United States and 13,598 MW worldwide in 1999. Wind installations have grown in the United States at an average rate of 15% in the past ten years. Installed capacity expanded by nearly 10% in the United States during 2002 to 4685 MW, with 410 MW of new equipment going into use that year. Worldwide installations currently total 39 GW.
- U.S. energy generation from wind was nearly 11 TWh out of a worldwide total of 69 TWh in 2003 up from 4.5 TWh out of an approximate total of 26 TWh in 1999.

- The top ten states had between 2,000 MW and 176 MW of large wind-turbine capacity at the end of 2003.
- In the United States, the wind industry is thinly capitalized, except for the acquisition of Enron Wind Corporation by General Electric Co. About six manufacturers and six to 10 developers characterize the U.S. industry.
- Enron Wind Corporation has been acquired by General Electric Corporation, Power Turbine Division.
- In Europe, there are about 12 turbine manufacturers and about 20 to 30 project developers. European manufacturers have established North American manufacturing facilities and are actively participating in the U.S. market.
- Current leading wind companies and sales volume are shown below:

	U.S. Market (2003)		World Market (2003)	
	<u>MW</u>	<u>Percent</u>	<u>MW</u>	<u>Percent</u>
Vestas (DK)	347	20.9	1,812	21.7
GE Wind (USA)	874	52.6	1,503	18
Enercon (D)	-	-	1218	14.6
Gamesa (ESP)	55	3.3	956	11.5
NEG Micon (DK)	146	8.8	855	10.2
Bonus (DK)	15	0.9	552	6.6
Repower (D)	-	-	291	3.5
MADE (ESP)	-	-	243	2.9
Nordex (DK)	-	-	242	2.9
Mitsubishi (JP)	201	12.1	218	2.6
Others	-	-	441	5.3

Sources: U.S. Market: NREL estimate based on BTM Consult, ApS, "World Market Update 2003",  
World Market: BTM Consult, ApS, "World Market Update 2003"

### **Technology History**

- Prior to 1980, DOE sponsored, and NASA managed, large-scale turbine development – starting with hundred-kilowatt machines and culminating in the late 1980s with the 3.2-MW, DOE-supported Mod-5 machine built by Boeing.
- Small-scale (2-20 kW) turbine development efforts also were supported by DOE at the Rocky Flats test site. Numerous designs were available commercially for residential and farm uses.
- In 1981, the first wind farms were installed in California by a small group of entrepreneurial companies. PURPA provided substantial regulatory support for this initial surge.
- During the next five years, the market boomed, installing U.S., Danish, and Dutch turbines.
- By 1985, annual market growth had peaked at 400 MW. Following that, federal tax credits were abruptly ended, and California incentives weakened the following year.
- In 1988, European market exceeded the United States for the first time, spurred by ambitious national programs. A number of new companies emerged in the U.K. and Germany.
- In 1989, DOE's focus changed to supporting industry-driven research on components and systems. At the same time, many U.S. companies became proficient in operating the 1,600 MW of installed capacity in California. They launched into value engineering and incremental increases in turbine size.
- DOE program supported value-engineering efforts and other advanced turbine-development efforts.
- In 1992, Congress passed the Renewable Energy Production Tax Credit (REPT), which provided a 1.5 cent/kWh tax credit for wind-produced electricity. Coupled with several state programs and mandates, installations in the United States began to increase.
- In 1997, Enron purchased Zond Energy Systems, one of the value-engineered turbine manufacturers. In 2002, General Electric Co. purchased Enron Wind Corporation.
- In FY2001, DOE initiated a low wind-speed turbine development program to broaden the U.S. cost-competitive resource base.

## Technology Future

The levelized cost of electricity for wind energy technology is projected to be:

	<u>2000</u>	<u>2002</u>	<u>2010</u>	<u>2020</u>
Class 4	6.0	5.5	3.0	2.7
Class 6	4.2	4.0	2.4	2.2

Assumptions include: 30-year levelized cost, constant January 2002 dollars, generation company ownership/financial assumptions; wind plant comprised of 100 turbines; no financial incentives included.

Source: FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001

- Wind energy's competitiveness by 2005 will be affected by policies regarding ancillary services and transmission and distribution regulations. Substantial cost reductions are expected for wind turbines designed to operate economically in low wind-speed sites, which will increase the amount of economical wind resource areas by 20-fold, and will be within 100 miles of most load centers.
- Initial lower levels of wind deployment (up to 15–20% of the total U.S. electric system capacity) are not expected to introduce significant grid reliability issues. Inasmuch as the wind blows only intermittently, intensive use of this technology at larger penetrations may require modification to system operations or ancillary services. Transmission infrastructure upgrades and expansion will be required for large penetrations of wind energy to service major load centers.
- Over the long term, as more high wind sites become used, emphasis will shift toward installation in lower wind-speed sites. Advances in technology will include various combinations of the following improvements, accomplished through continuing R&D:

*Towers* – taller for more energy, softer to shed loads, advanced materials, and erection techniques to save cost.

*Rotors* – Improving airfoils and plan forms to increase energy capture. For instance, a variable rotor diameter; larger rotors at the same cost or small cost increase by optimizing design and manufacturing, using lighter materials, and implementing controls to mitigate loads.

*Drive Train and Generators* – New designs to reduce weight and cost. Advances in power electronics and operational algorithms to optimize drive-train efficiencies, especially by increasing low efficiencies in ranges of operation that are currently much lower than those in the peak range. In addition to new power electronics and operational approaches, possible advances include permanent magnet generators, and use of single-stage transmissions coupled with multiple smaller, simpler, off-the-shelf generators that can be purchased from high-volume manufacturers.

*Controls* – By reducing loads felt throughout the turbine, various approaches for passive and active control of turbines will enable larger, taller structures to be built for comparatively small cost increases, resulting in improvements in system cost of energy.

*Design Codes* – Reductions in design margins also will decrease the cost of turbines and allow for larger turbines to be built for comparatively small increases in cost, resulting in improvements in system cost of energy.

*Foundations* – New designs to lower cost.

*Utility Grid Integration* – Models and tools to analyze the steady and dynamic impact and operational characteristics of large wind farms on the electric grid will facilitate wind power integration. Improved wind forecasting and development of various enabling technologies will increase the value of wind power.

**Source:** National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term.* DOE/PI-0002. November 2003

# Wind

## Market Data

Grid-Connected Wind Capacity (MW)	Source: Reference IEA (data supplemented by <i>Windpower Monthly</i> , April 2001), 2001 data from <i>Windpower Monthly</i> , January 2002, 2002 data from AWEA "Global Wind Energy Market Report 2004".											
Cumulative	<b>1980</b>	<b>1985</b>	<b>1990</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>
U.S.	10	1,039	1,525	1,770	1,794	1,741	1,890	2,455	2,554	4,240	4,685	6,374
Germany	2	3	60	1,137	1,576	2,082	2,874	4,445	6,095	8,100	11,994	14,609
Spain	0	0	9	126	216	421	834	1,539	2,334	3,175	4,825	6,202
Denmark	3	50	310	630	785	1,100	1,400	1,752	2,338	2,417	2,889	3,110
Netherlands	0	0	49	255	305	325	364	416	447	483	693	912
Italy			3	22	70	103	180	282	427	682	788	904
UK	0	0	6	193	264	324	331	344	391	477	552	649
Europe	5	58	450	2,494	3,384	4,644	6,420	9,399	12,961	16,362	23,308	28,706
India	0	0	20	550	820	933	968	1,095	1,220	1,426	1,702	2110
Japan	0	0	1	10	14	7	32	75	121	250	415	686
Rest of World	0	0	6	63	106	254	315	574	797	992	1,270	1,418
World Total	15	1,097	2,002	4,887	6,118	7,579	9,625	13,598	17,653	23,270	31,128	39,294

Installed U.S. Wind Capacity (MW)	Source: <i>Renewable Energy Project Information System (REPiS)</i> , Version 7, NREL, 2003.											
	<b>1980</b>	<b>1985</b>	<b>1990</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b> <sup>2</sup>
Annual	0.023	337	154	37	8	8	173	695	124	1,843	454	12
Cumulative <sup>1</sup>	0.060	674	1,569	1,773	1,781	1,788	1,961	2,656	2,780	4,623	5,078	5,090

<sup>1</sup> There are an additional 48 MW of wind capacity that are not accounted for here because they have no specific online date.

<sup>2</sup> 2003 data not complete as REPiS database is updated through 2002.

Annual Market Shares	Source: US DOE- 1982-87 wind turbine shipment database; 1988-94. DOE Wind Program Data Sheets; 1996-2000 American Wind Energy Association								
	<b>1980</b>	<b>1985</b>	<b>1990</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>
U.S. Mfg Share of U.S. Market	98%	44%	36%	67%	NA	38%	78%	44%	0%
U.S. Mfg Share of World Market	65%	42%	20%	5%	2%	4%	13%	9%	6%

State-Installed Capacity	Source: American Wind Energy Association. <a href="http://www.awea.org/projects/index.html">http://www.awea.org/projects/index.html</a>											
Annual State-Installed Capacity (MW)												
Top 10 States	<b>1980</b>	<b>1985</b>	<b>1990</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>
California*		N/A	N/A	3	0	8.4	0.7	250	0	67.1	108	198.8
Texas		0	0	41	0	0	0	139.2	0	915.2	0	197.5
Minnesota		0	0	0	0	0.2	109.2	137.6	17.8	28.6	16.8	228.2
Iowa		0	0	0.1	0	1.2	3.1	237.5	0	81.8	98.5	49.8
Wyoming		0	0	0	0.1	0	1.2	71.3	18.1	50	0	144
Oregon		0	0	0	0	0	25.1	0	0	132.4	60.9	41
Washington		0	0	0	0	0	0	0	0	178.2	50.0	15.6
Colorado		0	0	0	0	0	0	21.6	0	39.6	0	162.0
New Mexico		0	0	0	0	0	0	1.3	0	0	0	204.0
Oklahoma		0	0	0	0	0	0	0	0	0	0	176.3
Total of 10 States		N/A	N/A	44	0	10	139	859	36	1,493	334	1,417
Total U.S.		N/A	N/A	44	1	16	142	884	67	1,694	410	1669.1

Top 10 States	<b>1980</b>	<b>1985</b>	<b>1990</b>	<b>1995</b>	<b>1996</b>	<b>1997</b>	<b>1998</b>	<b>1999</b>	<b>2000</b>	<b>2001</b>	<b>2002</b>	<b>2003</b>
California*		N/A	N/A	1,387	1,387	1,396	1,396	1,646	1,646	1,714	1,822	2,043
Texas		0	0	41	41	41	41	180.2	180.2	1095.5	1095.5	1,293
Minnesota		0	0	25.7	25.7	25.9	135.1	272.7	290.5	319.1	335.9	563
Iowa		0	0	0.7	0.8	2	5	242.5	242.5	324.2	422.7	471
Wyoming		0	0	0	0.1	0.1	1.3	72.5	90.6	140.6	140.6	285
Oregon		0	0	0	0	0	25.1	25.1	25.1	157.5	218.4	259
Washington		0	0	0	0	0	0	0	0	178.2	228.2	244
Colorado		0	0	0	0	0	0	21.6	21.6	61.2	61.2	223
New Mexico		0	0	0	0	0	0	1.3	1.3	1.3	1.3	207
Oklahoma		0	0	0	0	0	0	0	0	0	0	176
Total of 10 states		N/A	N/A	1,454	1,455	1,465	1,604	2,462	2,498	3,992	4,326	5,763
Total U.S.	10	1,039	1,525	1,697	1,698	1,706	1,848	2,511	2,578	4,275	4,685	6,374

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1. Wind capacity in 2002 will be revised upward to at least 4.4 million kilowatts, as the Energy Information Administration continues to identify new wind facilities.

Annual Generation from Cumulative Installed Capacity (Billion kWh)	Source: U.S. - EIA, <i>Annual Energy Review 2003</i> , DOE/EIA-0384(2003) (Washington, D.C., September 2004), Table 8.2a; IEA R&D Wind Countries - IEA Wind Energy Annual Reports, 1995-2003. IEA Total - "Renewables Information 2002", IEA, 2002.
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2. Data for International Energy Agency R&D Wind Countries through 2001 included 16 IEA countries. Ireland and Switzerland were added in 2002 and Portugal was added in 2003.

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## Technology Performance

			Source: <i>U.S.DOE Wind Program, 1980-1995, FY03 U.S.DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020</i>								
Energy Production			1980	1985	1990	1995	2000	2005	2010	2015	2020
	Capacity Factor (%)	Class 4		10	15	20	25.2	32.6	44.7	46.5	47.1
		Class 6		20	22	25	39.4	44.3	49.6	50.9	53.8
	Specific Energy (kWh/m <sup>2*</sup> )	Class 4		500	800	850	900	1,110	1,260	1,310	1,330
		Class 6		900	1,150	1,300	1,400	1,650	1,700	1,740	1,760
	Production Efficiency** (kWh/kW)	Class 4	200	650	1,300	1,750	2,200	2,860	3,500	3,600	3,600
		Class 6	800	1,700	1,900	2,200	3,450	3,880	4,350	4,450	4,700

\* m<sup>2</sup> is the rotor swept area.

\*\* Production Efficiency is the net energy per unit of installed capacity.

Cost (Jan. 2002 dollars)		Source: FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001.									
		1980	1985	1990	1995	2000	2005	2010	2015	2020	
Project Cost (\$/kW)	Class 4					1,000	915	910	880	860	
	(Overnight costs)	Class 6				1,000	900	800	770	750	
O&M (\$/kW)	Class 4					11.0	7.9	7.0	6.9	6.6	
		Class 6				17.3	8.0	7.8	7.6	7.5	
Fixed O&M & Land (\$/kW)	Class 4					8.0	8.0	8.0	8.0	8.0	
		Class 6				8.0	8.0	8.0	8.0	8.0	

Specific Cost* (Project Capital Cost Per Rotor Captured Area - \$/m2) (Jan. 2002 dollars)		Source: <i>FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020.</i>									
		1980	1985	1990	1995	2000	2005	2010	2015	2020	
	Class 4					382	357	293	283	277	
	Class 6					414	340	312	300	276	

Levelized Cost of Energy* (\$/kWh)		Source: <i>U.S. DOE Wind Program 1980-1985; FY03 U.S. DOE Wind Program Internal Planning Documents, Summer 2001, 2000-2020</i>									
(Jan. 2002 dollars)		1980	1985	1990	1995	2000	2005	2010	2015	2020	
	Class 4			0.12	0.080	0.060	0.041	0.030	0.028	0.027	
	Class 6			0.08	0.060	0.042	0.027	0.024	0.023	0.022	

\* 30-year term. Generation Company Ownership/Financial Assumptions. Wind plant comprised of 100 turbines. No financial incentives are included.